Testing the Theoretical Mass-Radius Relation for White Dwarfs

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We present a detailed spectroscopic and photometric model atmosphere analysis of 158 white dwarfs for which precise trigonometric parallax measurements are available. The derived physical parameters are then compared to the predictions of the theoretical mass-radius relation for white dwarfs. We find that most of the stars in our sample are consistent with the mass-radius relation within a 1.5σ confidence level, thus providing strong support to the theory of stellar degeneracy. In some cases, significant discrepancies are observed, and we show that some of these objects are better explained in terms of unresolved double degenerate binaries. We also identify a few white dwarfs that are possibly composed of an iron core rather than a carbon/oxygen core.

Determination of Physical Parameters: The Spectroscopic and Photometric Techniques

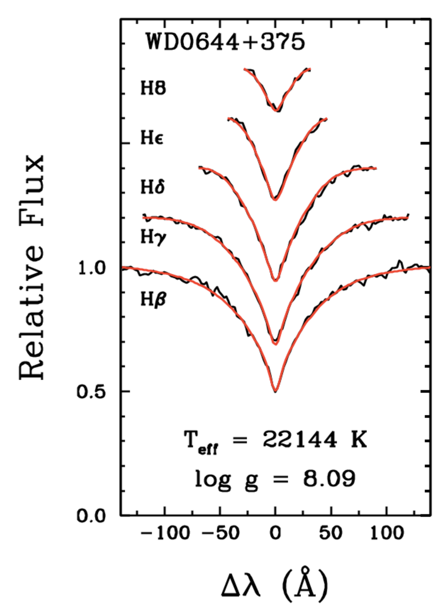


Figure 1 : The spectroscopic technique, pioneered by Bergeron et al. (1992), aims at determining the effective temperature (T_{eff}) and the surface gravity (log g) by comparing observed absorption line profiles to those predicted from model atmosphere calculations. The observed and model optical spectra are first normalized to a continuum set to unity, and the difference between the observed and predicted line shapes, defined as a χ^2 value, is then minimized using a nonlinear least-squares method, in order to obtain the best-fitting parameters T_{eff} and log g. The figure shows our best fit for the DA star WD0644+375 (G87-7). All Balmer lines from Hβ (bottom) to H8 (top) are fitted simultaneously. The observed and predicted line profiles are displayed in black and red, respectively, and the lines are offset vertically by 0.2 for clarity.

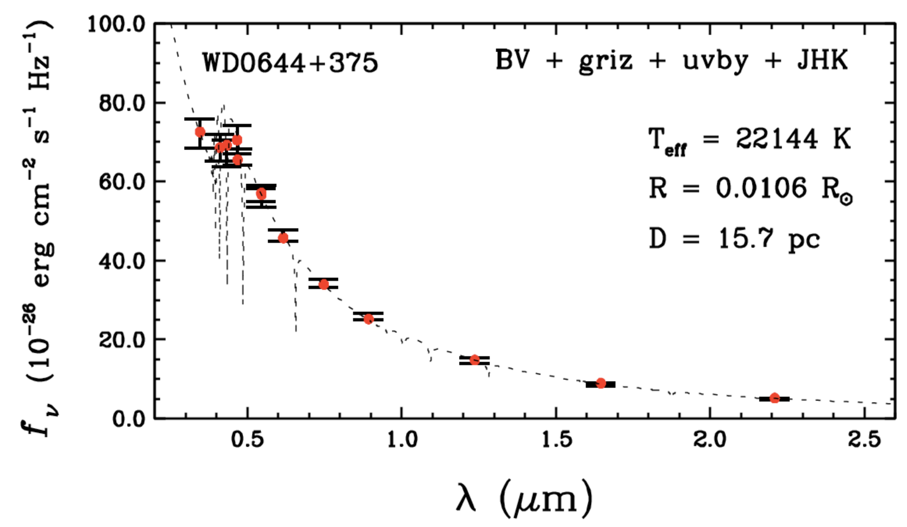


Figure 2 : The photometric technique, developed by Bergeron et al. (1997), involves comparing the observed and predicted spectral energy distributions, built from absolute fluxes averaged over different wavelength intervals. These observed (f) and model (H) fluxes are related by the equation

$$f = 4\pi(R/D)^2 H \qquad (1)$$

where R and D are the star's radius and distance from Earth, respectively. Note that the model fluxes H strongly depend on the effective temperature. Thus, T_{eff} and the ratio R/D can be obtained by minimizing the difference between observed and predicted average fluxes, defined as a χ^2 value, using a nonlinear least-squares method. Here, we set the temperature at the value obtained from the spectroscopic method and consider only the ratio R/D as a free parameter. Since the distance is known from trigonometric parallax measurements for all white dwarfs in our sample, the photometric technique yields the radius. The figure shows our best fit for the DA star WD0644+375 (G87-7). Observed fluxes are represented by black error bars, while model fluxes are displayed as red circles. The monochromatic model flux is also shown as the dotted line.

Test of the Mass-Radius Relation

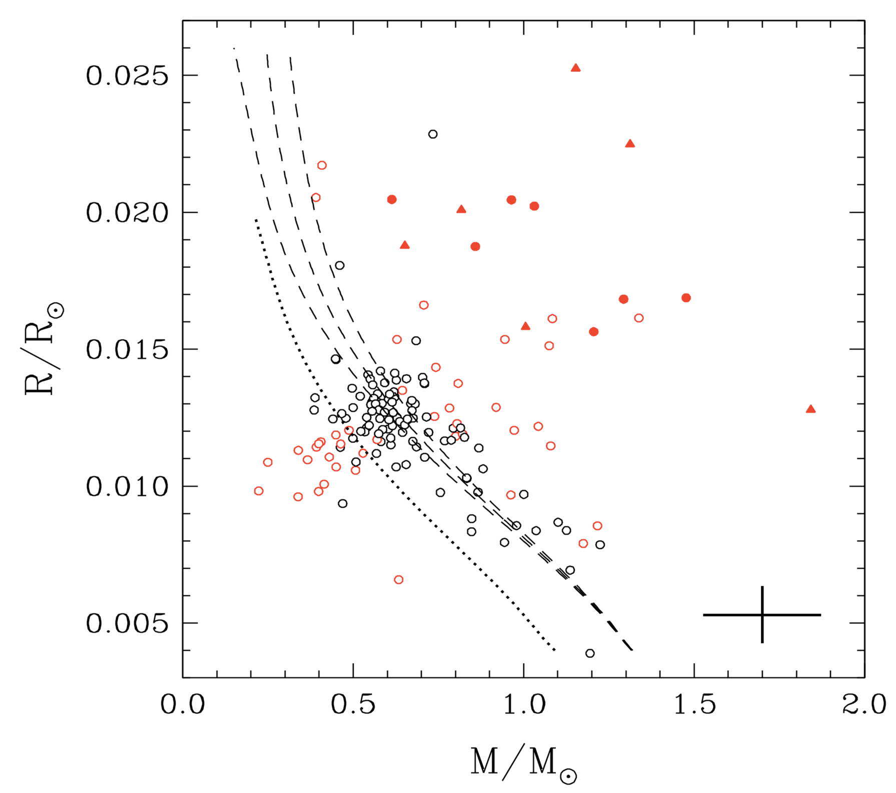


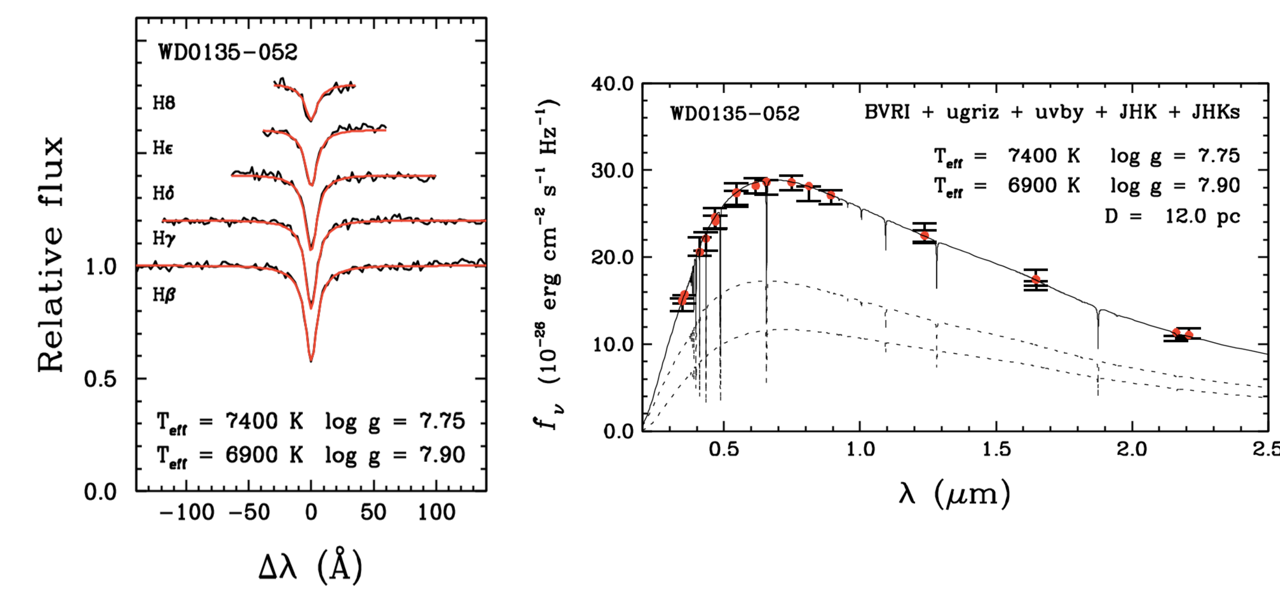
Figure 3 : The values of surface gravity and radius, derived respectively from spectroscopy and photometry, can be combined to provide the stellar mass M through the well-known relation

$$g = GM/R^2 \qquad (2)$$

where G is the gravitational constant. The radius and mass estimates can then be compared to the theoretical R versus M curve at the effective temperature determined from the spectroscopic fit, and for a given core composition and hydrogen layer thickness. These correspond to the input parameters of our white dwarf evolutionary models, described in Fontaine et al. (2001), from which the mass-radius relation can be computed. The figure presents the location of our 158 white dwarfs in the R versus M diagram, together with mass-radius relations for a carbon/oxygen core at T_{eff} = 7000, 15,000 and 25,000 K (dashed lines, from left to right), and for an iron core at T_{eff} = 15,000 K (dotted line), with a hydrogen envelope of $M_H/M = 10^{-4}$ in all cases. The average error bars are displayed in the lower right corner. Stars shown in red are inconsistent with the mass-radius relation for a C/O core within a 1σ confidence level. The filled red symbols represent known (triangles) and suspected (circles) double degenerate binaries. All in all, 75% of the objects in our sample are consistent with the mass-radius relation for a C/O core within 1.5σ. We investigate the most discrepant cases in what follows.

Double Degenerate Binaries

Figure 4 : Our sample contains six well-known unresolved double degenerate binaries, indicated by filled red triangles in Figure 3. As expected, when considered as single stars, these objects are at odds with the predictions from the mass-radius relation. It is possible, using modified versions of the spectroscopic and photometric techniques, to fit the observed optical spectra and energy distributions with composite models in order to obtain atmospheric parameters T_{eff} and log g for both components in such binary systems. This figure displays our best solution for the well-known double degenerate WD0135−052 (L870-2); the right panel shows the contribution of each component (dotted lines) to the total flux (solid line). Based on our analysis, we identified nine additional objects, shown as filled red circles in Figure 3, that are better interpreted as double degenerate binaries.



Iron-Core White Dwarfs

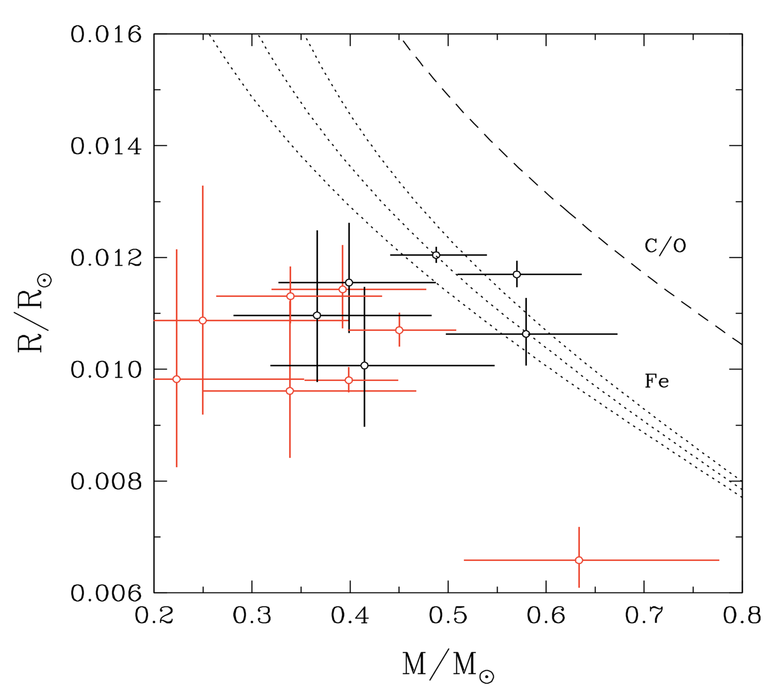
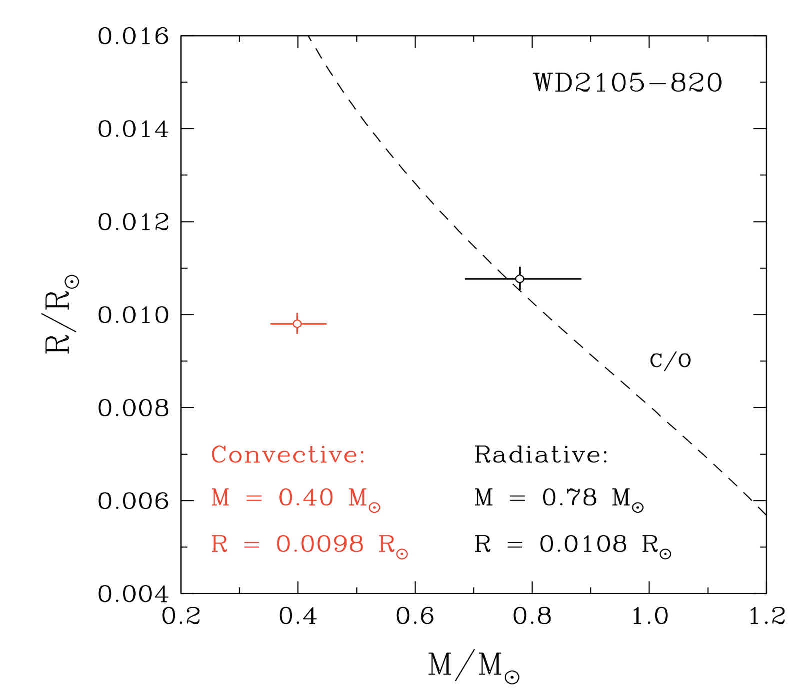


Figure 5 : As suggested by Figure 3, several objects in our study may be composed of an iron core rather than a carbon/oxygen core, since they fall closer to the Fe-core mass-radius relation. This figure shows the location in the R versus M diagram of the 14 such white dwarfs in our sample, together with mass-radius relations for an iron core and a hydrogen envelope of $M_H/M = 10^{-4}$ at T_{eff} = 7000, 15,000 and 25,000 K (dotted lines, from left to right). The C/O-core mass-radius relation at T_{eff} = 15,000 K (dashed line) is also displayed as a reference. Six stars (shown in black) are consistent with the Fe-core mass-radius relation within 1σ, while the other objects (shown in red) are located too far on the left in the diagram to fall on the Fe-core theoretical curve. Thus, for six white dwarfs, the scenario of an interior made of iron-rich material can be invoked to account for our discrepant results. This interpretation definitely challenges the current theories of white dwarf formation. One of these six Fe-core candidates is WD0644+375 (G87-7), for which our analysis confirms the Fe-core hypothesis first proposed by Provencal et al. (1998).

The Peculiar Case of WD2105−820

Figure 6 : Recent studies by Valyavin et al. (2014) and Tremblay et al. (2015) have shown that magnetic fields of only a few kG can suppress convective energy transport in white dwarf atmospheres. We report here compelling evidence that the DA star WD2105−820, which harbors a weak magnetic field (polar strength of ≈ 56 kG) according to Landstreet et al. (2012), most probably has a purely radiative atmosphere. We show in the present figure the location of WD2105−820 in the R versus M diagram using the physical parameters obtained from convective (red) and radiative (black) atmospheric models, together with the mass-radius relation for a C/O core and a hydrogen envelope of $M_H/M = 10^{-4}$. The agreement with the mass-radius relation is significantly better if we assume a radiative atmosphere. Thus, it is highly probable that convection is impeded by the magnetic field in the atmosphere of WD2105−820.



Conclusions

- Among a sample of 158 white dwarfs, we found that 89% of the stars either obey the theoretical mass-radius relation (75%) or show inconsistencies for which we can supply a physical explanation (14%). We can thus confidently assert that the theory of degenerate stars rests on solid empirical grounds.
- Our robust approach for testing the mass-radius relation allowed us to identify 15 known and suspected double degenerate binaries, six possible Fe-core white dwarfs, and one star in which convection is inhibited by a magnetic field.
- Our ability to investigate the degenerate mass-radius relation will be greatly improved by the upcoming data releases of the *Gaia* mission, which will significantly increase the number and precision of white dwarf trigonometric parallax measurements.

References

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